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(54) Title: OPTICAL WAVELENGTH MEASURING DEVICES
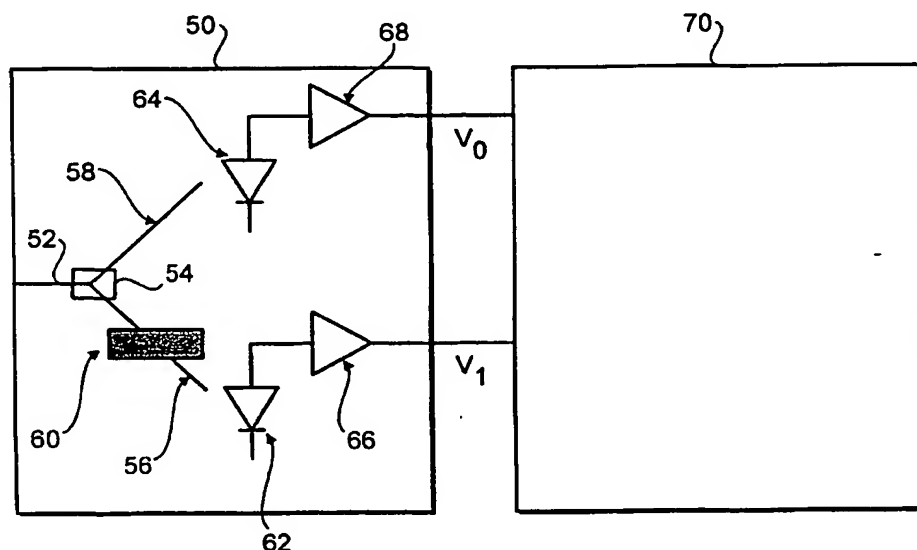
(57) Abstract: An optical wavelength measuring device, comprising: a beam splitter for receiving an input light beam and splitting it into at least first and second output light beams; at least first and second photodetectors; and integrated optical waveguide device defining at least first and second waveguide structures for receiving and guiding the first and second output light beams, respectively, to the first and second photodetectors, respectively, wherein at least the first waveguide structure includes a first modulation section having a periodic transmission-wavelength function; and a signal processor for determining the wavelength of the input light beam on the basis of the signal outputs from the first and second photodetectors.

OPTICAL WAVELENGTH MEASURING DEVICES

The present invention relates to optical wavelength measuring devices.

With the growth of optical communications, Wavelength Division Multiplexing (WDM) is valuable in making full use of optical bandwidth. An optical signal should lie on one of the regularly spaced wavelength channels which are permitted on the optical network. Dense Wavelength Division Multiplexing (DWDM) is used in optical systems having a channel spacing of 200GHz (1.6nm) or less.

The invention may provide a device which can measure the wavelength of an input optical signal for, for example, detecting which of the above-mentioned regularly spaced channels the optical signal lies in.

A known wavelength measuring device comprises a beam splitter which divides a single optical input into two outputs which are directed to a first photodiode and a second photodiode, respectively, the second photodiode being provided with a coating designed to give a ratio of electric signals from the two photodiodes which is a known function of wavelength over the response function of the photodiode. The average wavelength of the input optical signal can be calculated from the ratio of the electric signals produced by the two photodiodes.

However, a drawback with the known devices of this type is that they are relatively bulky and difficult to manufacture at low cost and high volume. A further drawback with the type of device described above employing coated photodiodes is that it has limited

design flexibility over the range of wavelengths normally under consideration in WDM applications. Furthermore, such devices are only of limited usefulness for accurately measuring wavelengths, and this is a particular problem in WDM applications since it may not be possible to measure the wavelength with the required high degree of accuracy. For example, the spectral resolution of the coatings on the photodiodes is generally limited to about 1nm, which is insufficient to identify or tune channels in a weak tap off a DWDM system.

The present invention provides an optical wavelength measuring device, comprising: a beam splitter for receiving an input light beam and splitting it into at least first and second output light beams; first and second photodetectors; an integrated optical waveguide device defining at least first and second waveguide structures for receiving and guiding the first and second output light beams, respectively, to the first and second photodetectors, respectively, wherein at least the first waveguide structure includes a first modulation section having a periodic transmission-wavelength function; and a signal processor for determining the wavelength of the input light beam on the basis of the signal outputs from the first and second photodetectors.

The term "periodic transmission-wavelength function" refers to any transmission-wavelength function based wholly or substantially on interference effects. The term "waveguide structure including a modulation section having a periodic transmission-wavelength function" includes waveguide structures for which only a fraction

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of a whole cycle is observed in practice as a result of absorption effects, for example.

In the context of a waveguide, the term "beam" refers to a waveguide mode or mode.

The beam splitter may be an evanescent coupler, a multi-mode interference (MMI) coupler, or a Y-junction.

The modulation section having a periodic transmission-wavelength function may, for example, comprise a waveguide Fabry-Perot cavity, an air-gap Fabry-Perot cavity, a Path-Imbalanced Mach-Zender (PIMZ), a grating etched into the waveguide and or its immediate surroundings, an arrayed waveguide grating or a grating demultiplexers.

The photodetectors may, for example, be InGaAs/InP based PIN photodiodes. Other photodiodes such as avalanche photodiodes (APD), thermal micro-bolometers or CCD devices may also be used. These may be attached in proximity to the waveguide ends with or without the use of etched mirrors to aid convenience of attachment. Alternatively, they may be fully integrated with the waveguides by use of standard integrated optic wafer processing techniques.

In a preferred embodiment of the invention, the beam splitter and the integrated optical waveguide device are defined in a single silicon chip, and the photodetectors are attached to a surface of the silicon chip. In this preferred embodiment, the photodetectors could comprise polished facets at an end of the silicon chip, or

photodiode holes incorporating turning mirrors etched
into the silicon chip.

Embodiments of the present invention will be described
hereunder, by way of example only, with reference to the
accompanying drawings, in which:-

Figure 1 shows a schematic cross-sectional view of a
typical silicon waveguide;
Figures 2 to 6 are schematic plan views of examples of
wavelength-dependent waveguide structures for use in the
device of the present invention;
Figure 7 is a schematic view of an embodiment of the
device of the present invention; and
Figures 8 to 11 show typical transmission-wavelength
functions   of   the   wavelength-dependent   waveguide
structures used in the present invention for explaining
the method of determining wavelength using a device
according to the present invention.

Embodiments of the device of the present invention will
be described hereunder with general reference to Figure 1
which shows a schematic cross-sectional view of the basic
structure of a typical silicon waveguide taken through a
plane perpendicular to the direction in which the optical
wave is to be guided. In Figure 1, the silicon waveguide
6 is formed on a buried oxide layer 4 which is in turn
formed on a silicon substrate 2. A silica cladding 8 is
formed over the silicon waveguide 6.

The waveguide structures used in the embodiments of the
present invention described hereunder are based on
modifications of this basic structure.

In Figures 2 to 6, the arrows indicate the direction of travel of the optical wave from beam splitter to the photodetector.

With reference to Figure 2, the waveguide structure including a modulation section comprises two silicon waveguide sections 10, 12 separated by an air gap 14. Such a waveguide structure can be formed by etching a slot into a straight waveguide. The air gap 14 functions as a Fabry-Perot resonant cavity. A bare Si-air interface giving a reflectivity of 0.33 can give a spectral response which is modulated by 70% or higher.   It provides a relatively low degree of wavelength selectivity over a relatively large wavelength range.
The finesse of the resonant cavity can be improved using a waveguide structure as schematically shown in Figure 3 in which the faces of the ends of the two waveguide sections 10, 12 which define the resonant cavity are each provided with a reflective coating 16. The reflective coating 16 may, for example, consist of a layer of a dielectric such as an oxide or nitride deposited to an appropriate thickness by, for example, low pressure chemical vapour deposition (LPCVD). The resulting increase in modulation of the spectral response improves the signal-to-noise ratio thereby increasing the finesse of the resonant cavity.

For longer length cavities for fine wavelength discrimination, the waveguide structures shown in Figures 4 or 5 are preferably adopted.   In Figure 4, the waveguide structure comprises three waveguide sections 18, 20, 22 arranged in series and separated by two air gaps 28, 30.   In this waveguide structure, the middle waveguide section 20 functions as a Fabry-Perot resonant

cavity. In use, the light is resonantly reflected between the two faces 24, 26. The faces 25, 27 of the ends of the first and third sections 18, 22 adjacent the air gaps 28, 30 are angled with respect to the beam path to prevent the air gaps themselves from functioning as resonant cavities. The waveguide structure shown in Figure 5 is exactly the same as that shown in Figure 4 except that the faces 24, 26 of the second section 28, 30 are provided with reflective coatings 32, 34.

An alternative structure for the waveguide structure including a modulation section is schematically shown in Figure 6. In this waveguide structure, two waveguides 38, 40 of differing optical path lengths are connected to a beam splitter 42 and a beam combiner 44. In use, the beam splitter 42 divides the light beam into the two waveguides 38, 40, and the beam combiner 44 recombines the two light beams from the respective waveguides 38, 40. This waveguide structure functions as a Path Imbalanced Mach-Zender (PIMZ) interferometer. Two waveguides define paths between two couplers. One path contains curves or mirrors so that it is of greater length than the other. The difference in path length defines the relative phase of light from the two waveguides, and hence the superposition of amplitudes which leave through one output waveguide of the PIMZ. The outputs oscillate sinusoidally with optical frequency according to the equations below. This defines the periodic transmission function.

$$I_{out1}(F) = I_{in} \sin^2\left(\frac{FL\pi}{c}\right) \qquad\qquad I_{out2}(F) = I_{in} \cos^2\left(\frac{FL\pi}{c}\right)$$

The output of the two waveguides is given by these
equations. The output of the second waveguide is lost if
a Y junction is used as the coupler or transmitted to a
second waveguide if an evanescent coupler is used.

In these equations, F is the optical frequency in Hz; c
is the speed of light; I is intensity; L is the effective
path length difference which is given by the product μl,
where μ is the effective refractive index of the
waveguide and l is the physical length of the path
difference.

This function is conveniently periodic in frequency,
which allows the structure to be designed with path
imbalance L which causes the maxima of $I_{out1}(F)$ to lie on a
chosen grid of optical frequencies commonly used in
optical communications.

In a preferred embodiment of the device of the present
invention, the beam splitter is provided together with
the waveguide structures as an integral part of the
integrated optical waveguide device, as shown
schematically in Figure 7. Figure 7 shows a schematic
plan view of a simple device comprising a silicon chip 50
defining a receiving waveguide 52, a beam splitter 54,
and two waveguide structures 56, 58, one of which
includes a periodic modulation section 60 of one of the
types described above, for example. Two photodiodes 62,
64 are provided on the silicon chip 50 and are
electrically connected to transimpedance amplifiers 66,
68 also provided on the silicon chip.

The photodetectors may, for example, be polished facets at an end of the chip, or photodiode holes incorporating turning mirrors etched into the chip.

The signal processor 70 determines the wavelength on the basis of the signals V0, V1 received from the amplifiers 66, 68.

The integrated beam splitter 54 defined by the silicon chip 50 may be, for example, a Y branch, an evanescent coupler, a multi-mode interference coupler or a fused coupler.   All these couplers suffer from a slight dependence on wavelength, and this has to be taken into account in the signal processing to determine the wavelength of the incident beam.   The signal processing is simplified if the beam splitter is wavelength independent.

The inlet of the receiving waveguide 52 is preferably provided with a V-groove fiber slot (not shown) defined in the silicon chip to facilitate the connection of an optical fiber.

The photodiodes 62, 64 are separate components mounted on the silicon chip 50. They are properly aligned with the output ends of the respective waveguide structures by means of three-dimensional photodiode alignment features (not shown) formed on the surface of the silicon chip 50, such as described in GB2315595 in the name of the applicant.

Amplifiers 66, 68 such as integrated transimpedance amplifiers are attached to the integrated optical device to interface from the respective photodiode currents to

voltage sensitive threshold logic gates or to transmission lines leaving the silicon chip 50. Other electronic or optical structures can also be defined in, or mounted on, the silicon chip as required.

The method of determining the wavelength of an input light beam will now be explained with reference to Figures 8 to 11. In the case of a simple dual detector, as shown schematically in Figure 7, having two waveguide structures having different wavelength transmission functions, the ratio of voltages $V1/V0$ from the transimpedance amplifiers connected to the respective photodiodes is determined by the ratio of the transmission functions of the two waveguide structures. A coarse wavelength modulation selection element (i.e. one having relatively weak wavelength dependence such as a relatively narrow air cavity) will, for example, display a transmission-wavelength function of the kind shown in Figure 8 which has normalised transmission on the y-axis and wavelength on the x-axis. Given a stored value of the known transmission functions of the two waveguide structures, the measured ratio $V1/V0$ can be appropriately processed to obtain a wavelength measurement to a degree of accuracy represented by band A-B whose width is determined by noise from the detectors, shot noise in the incident light, and uncertainty in the transmission function.

For some applications, a small uncertainty in the transmission function or noise in the detector signal leads to unacceptable error in the wavelength measurement from a dual detector system. For example, WDM systems often require determination of wavelength to better than 0.4nm. In such cases, it is necessary to use an optical

wavelength measurement device in which the beam splitter divides the incident light beam into more than two beams, the additional beams being directed to additional photodetectors via additional waveguide structures including modulation sections of increased wavelength dependence, i.e. modulation sections having periodic wavelength-transmission functions of increased frequency.

The transmission function of a third waveguide structure displaying increased wavelength dependence compared to the first and second waveguide structures is shown in Figure 9. The signal from the photodiode connected to this third waveguide structure can be used to provide an improved estimate of the wavelength. It is known from the signal ratio V1/V0 from the first and second photodiodes that the wavelength lies within the relatively broad band A-B. Since the wavelength dependence of the third waveguide structure is greater than the second waveguide structure, it can be determined from the signal from the third photodiode that the wavelength lies within a narrower band C-D. The width of this band will again depend on the factors described above for the width of band A-B.

If further accuracy is required, a fourth parallel waveguide structure of further increased wavelength dependence connected to a fourth photodiode can be provided. With reference to Figure 10 (which is an expanded view of the relevant section of Figure 9) and Figure 11, which shows the transmission function for the fourth waveguide structure, the wavelength of the incident radiation can be estimated to be within the narrow bandwidth E-F using the result shown in Figure 9 and the signal from the fourth photodiode.

Ambiguous measurements may arise due to the maximum and minimum turning points in the fine transmission function. For applications of the wavelength measuring device such as monitoring the wavelength of a continuously tuneable laser, such ambiguous measurements near to the maxima and minima of the fine transmission function can pose a serious limitation. One way to solve this is to provide a further parallel fine modulation section connected to a further photodetector, the further fine modulation section designed to give a duplicate transmission function having turning points offset by a quarter cycle so that if the output from the first fine modulation section gives an ambiguous result due to the input wavelength falling on a turning point, then the output from the further fine modulation section can be used to obtain a more accurate result. One alternative is to use a birefringent waveguide of the appropriate length which gives a transmission function for TE, and a quarter-cycle offset transmission function for TM. If the transmission function for TE gives an ambiguous result, then the transmission function for TM can be used by switching the polarisation to obtain a more accurate result.

In most optical communication systems, the light source is tuned to obtain the desired wavelength. The wavelength measuring device of the present invention may also be used to provide closed-loop feedback to a tuning control circuit for the light source, or may send instructions to retune a remote light source. Furthermore, it may also be used to transmit a remote alarm if light of a wavelength that deviates from the desired grid of wavelengths is measured.

In the case the input light beam whose wavelength is to
be measured is produced by a continuously tuneable laser,
the signal processor could be programmed to control the
laser on the basis of the measured wavelength until the
laser produces a light beam of the desired wavelength.

When a waveguide structure having a PIMZ type modulation
section is used, the inclusion of a phase modulation
component with the PIMZ type modulation section makes it
possible to also measure the bandwidth of the input light
beam.   The phase modulation component may be a thermal
phase modulator or a P-N diode phase modulator such as
the ASOC® phase modulator produced by Bookham Technology
Limited.

Generally, the provision of more than three detectors
(with the second and third detectors achieving an order
of magnitude better wavelength selectivity than the first
and second detectors, respectively) is desirable if the
signal-to-noise ratio is moderate i.e. about 10:1 or
greater.   Such a three detector system is sufficient to
obtain an average of 0.1nm resolution across a 100nm
region provided that the signal-to-noise ratio is 10 or
greater.

High finesse Fabry-Perot type modulation sections are
preferred if the input light beam is expected to have a
narrow bandwidth, and is expected to lie on one of a set
of well-defined regular frequency-spaced channels, since
these give the maximum wavelength accuracy.   If the input
wavelength bandwidth is expected to exceed 0.2 times the
channel spacing, then a PIMZ-type modulation section is
preferred.

CLAIMS

1.   An   optical   wavelength   measuring   device,
comprising:

a beam splitter for receiving an input light beam
and splitting it into at least first and second output
light beams;

at least first and second photodetectors;

an integrated optical waveguide device defining at
least first and second waveguide structures for receiving
and guiding the first and second output light beams,
respectively, to the first and second photodetectors,
respectively, wherein at least the first waveguide
structure includes a first modulation section having a
periodic transmission-wavelength function;

and   a   signal   processor   for   determining   the
wavelength of the input light beam on the basis of the
signal outputs from the first and second photodetectors.

2.   An optical wavelength measuring device according to
claim 1 wherein the beam splitter is an integral part of
the integrated optical waveguide device.

3.   An optical wavelength measuring device according to
claim 1 or claim 2 wherein the beam splitter is adapted
for splitting the input light beam into at least first,
second and third output light beams; the integrated
optical   waveguide   device   further   defines   a   third
waveguide structure for receiving and guiding the third
light beam to a third photodetector, the third waveguide
structure including a second modulation section having a
periodic   transmission-wavelength   function   which   differs
from   the   first   modulation   section;   and   the   signal

processor for determining the wavelength of the input light beam does so on the basis of the signal outputs from the first, second and third photodetectors.

4.   An optical wavelength measuring device according to claim 3 wherein the second modulation section having a periodic transmission-wavelength function which has a greater frequency than that of the first modulation section.

5.   An optical wavelength measuring device according to any preceding claim wherein the first waveguide structure comprises two solid waveguide sections arranged in series and having parallel opposing endfaces defining a gap therebetween, wherein the opposing endfaces are perpendicular to the beam path direction.

6.   An optical wavelength measuring device according to claim 5 wherein the gap is filled with air.

7.   An optical wavelength measuring device according to claim 4 or claim 6 wherein the parallel opposing endfaces of the two solid waveguide sections of the first waveguide structure are each provided with reflective coatings.

8.   An optical wavelength measuring device according to claim 5 wherein the first waveguide structure includes first, second and third waveguide sections which are arranged in series and which define a first gap between opposing ends of the first and second waveguide sections and a second gap between the opposing ends of the second and third waveguide sections; the ends of the second waveguide section adjacent the first and second gaps

having parallel faces perpendicular to the beam path direction.

9.   An optical wavelength measuring device according to claim 8 wherein the faces of the ends of the second waveguide section adjacent the first and second gaps are each provided with a reflective coating.

10.   An optical wavelength measuring device according to claim 8 or claim 9 wherein the faces of the ends of the first and third waveguide sections adjacent the first and second gaps are angled with respect to the respective end faces of the second waveguide section adjacent the first and second air gaps.

11.   An optical wavelength measuring device according to claim 1 wherein the first waveguide structure comprises two waveguides of differing path lengths connected to the beam splitter and the first photodetector such that, in use, at least a fraction of the first output light beam is split into each of the two waveguides and then recombined before it reaches the first photodetector.

12.   An optical wavelength measuring device according to claim 1 wherein the beam splitter and the integrated optical waveguide device are defined in a single silicon chip.

13.   An optical wavelength measuring device according to claim 12 wherein the first and second photodetectors are formed in the silicon chip.

14.   An optical wavelength measuring device according to claim 13 wherein the first and second photodetectors comprise polished facets at an end of the silicon chip.

15.   An optical wavelength measuring device according to claim 13 wherein the first and second photodetectors comprise photodiode holes including turning mirrors etched into the silicon chip.

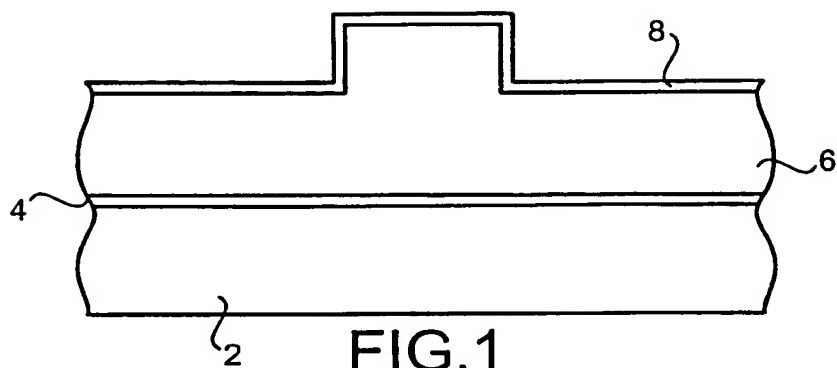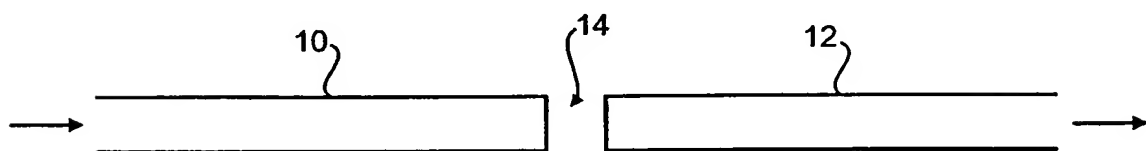16.   An optical wavelength measuring device substantially as hereinbefore described with reference to the accompanying drawings.

FIG.1

FIG.2

FIG.3

FIG.4

FIG.5

FIG.6

FIG.7
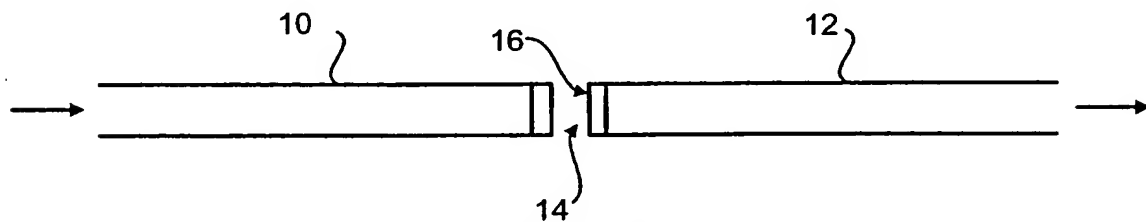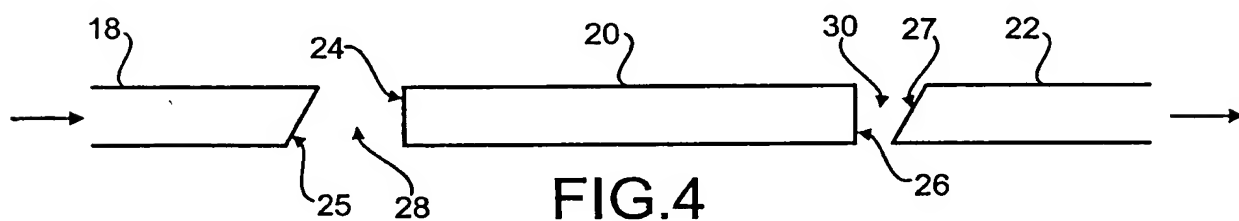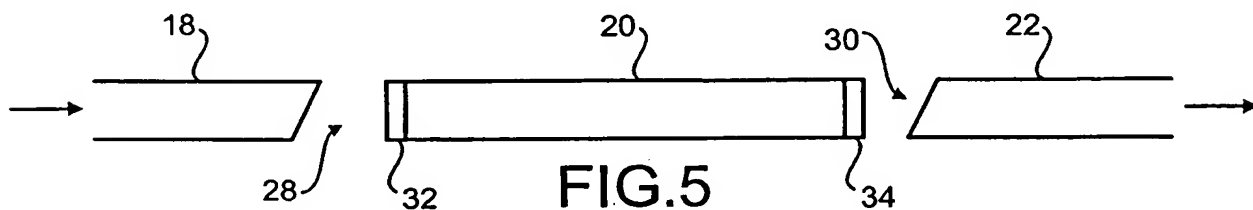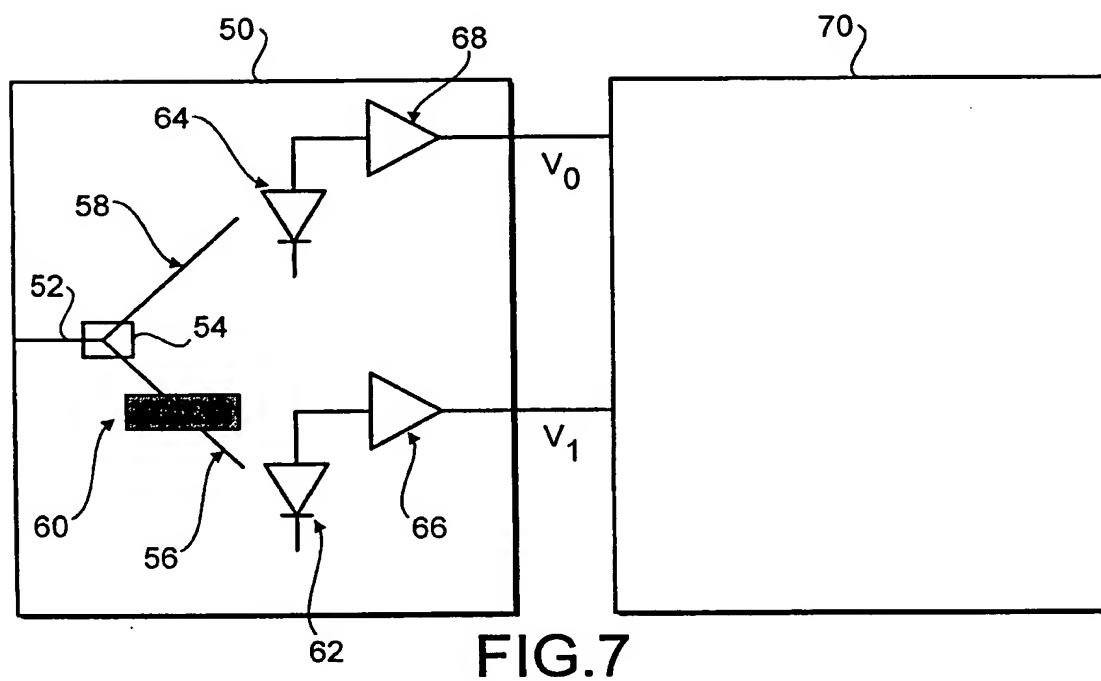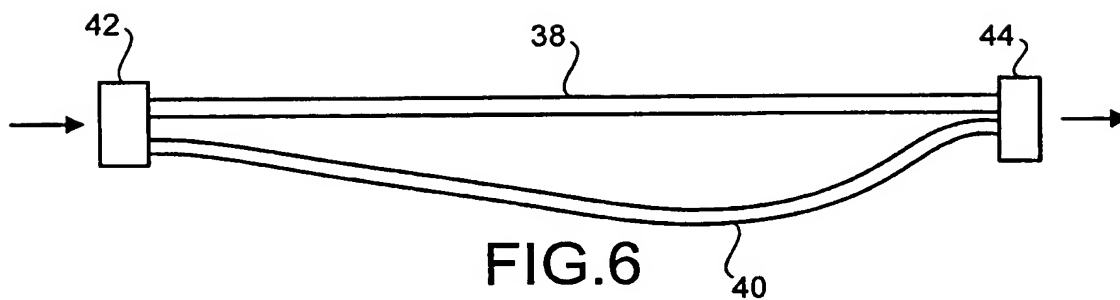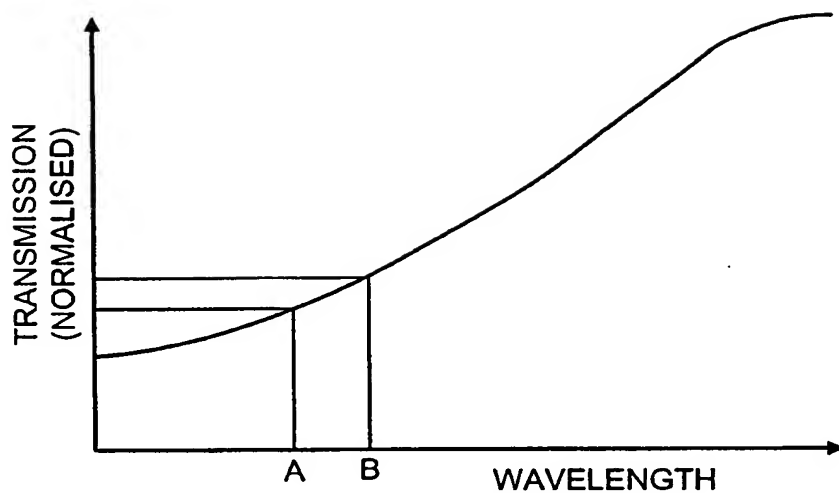
FIG.8
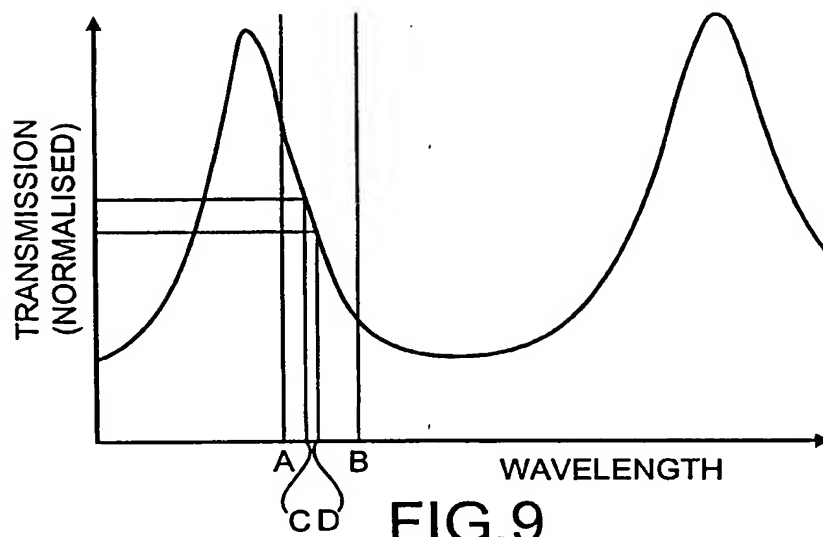
FIG.9

4 / 4
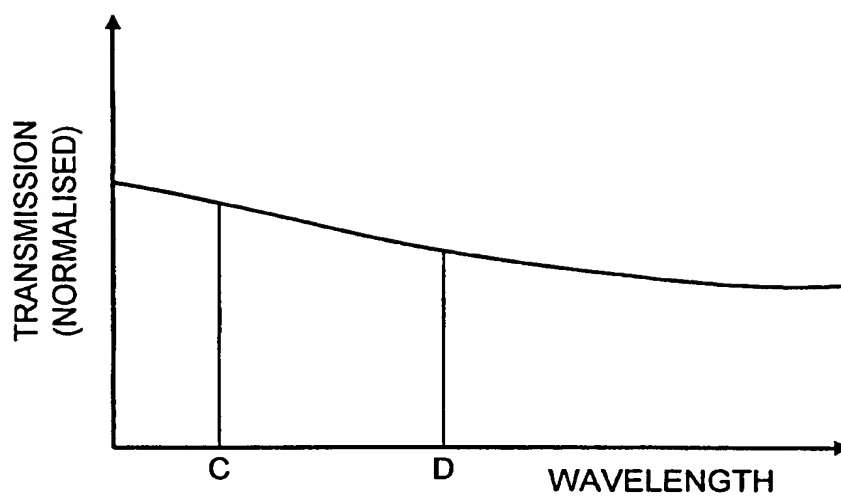
FIG.10

FIG.11

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01J9/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G01J   G01D   H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 798 859 A (IP JOSEPH ET AL) 25 August 1998 (1998-08-25)	1,2,16
Y	column 2, line 61 -column 3, line 15 figure 1	3,5-8

Y	US 5 729 347 A (SO VINCENT) 17 March 1998 (1998-03-17) column 1, line 64 -column 2, line 14 column 3, line 15 -column 5, line 65	3

Y	EP 0 300 640 A (AMERICAN TELEPHONE & TELEGRAPH) 25 January 1989 (1989-01-25) column 6, line 23 -column 8, line 55 figures 3,4	5-8

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[X] Further documents are listed in the continuation of box C.　　　　[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
20 November 2000	28/11/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Jacquin, J

Form PCT/ISA/210 (second sheet) (July 1992)

page 1 of 2

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 319 435 A (MELLE SERGE M ET AL) 7 June 1994 (1994-06-07) column 1, line 62 -column 2, line 8 column 4, line 20 -column 5, line 47 ---	1,2,16
X	WO 98 36252 A (NAKSTAD HILDE ;OPTOPLAN AS (NO); THINGBOE DAG (NO); KRINGLEBOTN JO) 20 August 1998 (1998-08-20) column 8, line 28 -column 9, line 22 figures 6A,6B ---	1,16
A	RAO Y-J: "IN.FIBRE BRAGG GRATING SENSORS" MEASUREMENT SCIENCE AND TECHNOLOGY,GB,IOP PUBLISHING, BRISTOL, vol. 8, no. 4, 1 April 1997 (1997-04-01), pages 355-375, XP000725109 ISSN: 0957-0233 figure 10A -----	1-16

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Information on patent family members

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